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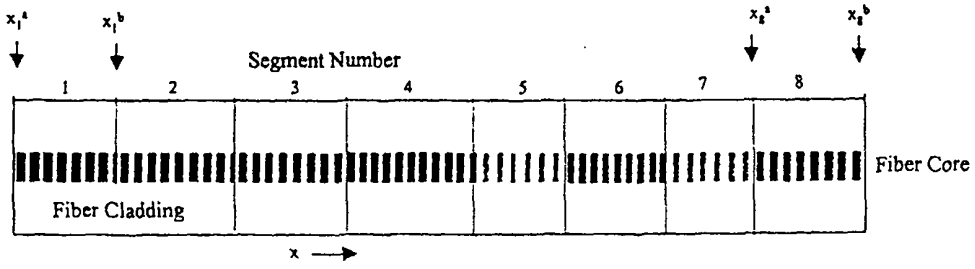

(57) Abstract

Segmented waveguide gratings are disclosed that include a plurality of grating segments or "subgratings" (1–8). The subgrating (1–8) are defined by periodic variations in an optical property of the waveguide, such as index of refraction or transmittance. A spectral transfer function of the segmented waveguide grating is defined by the subgratings, and the subgratings (1–8) can be selected to produce a cross–correlation of an optical input with a reference optical waveform, a specified temporal waveform, or a selected filtering function. The waveguide structures can be optical fibers, and the waveguide structures can be used as multiplexers/demultiplexers in optical communication systems. Methods for fabricating such segmented waveguides are disclosed.

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SEGMENTED COMPLEX FIBER GRATINGS

Field of the Invention

The present invention relates to complex fiber Bragg gratings and more particularly to the use of complex fiber gratings for spectral filtering, and for the use of complex fiber gratings in optical communication systems.

Background of the Invention

Optical fiber Bragg gratings are important elements for selectively transmitting or reflecting specific wavelengths of light within an optical fiber. A fiber Bragg grating comprises a length of optical fiber containing a refractive index profile that varies periodically along the length of the fiber. Refractive index variations with a single period, Λ, selectively reflect light with a wavelength of $\lambda = 2\Lambda$. Other wavelengths are transmitted essentially unimpeded. Alternatively, Λ can be chosen to vary along the length of the fiber in order to reflect a broad range of wavelength, e.g., chirped gratings. Such broadband gratings can, for example, be used for dispersion compensation to provide a wavelength-dependent time delay to a propagating signal with a finite bandwidth. Another class of fiber gratings comprises the long-period gratings in which the periodic spacing is at least 10 times larger than the transmitted wavelength, i.e. $\Lambda > 10\lambda$. These gratings provide wavelength-dependent losses by coupling optical power between co-propagating guided and non-guided modes. Long-period gratings remove selected wavelengths from the guided mode into the non-guided mode and consequently spectrally shape the transmitted beam (U.S. Pat. No. 5,764,829) while causing little back-reflection in the fiber. Fiber gratings in general have numerous applications in the areas of optical sensing, signal processing, spectral filtering, and optical communications.

Simple periodic fiber gratings are known in the art, and many different methods have been described for impressing refractive-index gratings in the core of photosensitive (e.g. germanium-doped) optical fibers (U.S. Pat. No. 4,474,427) including holographic techniques (U.S. Pat. No. 4,725,110), phase mask techniques (U.S. Pat. No. 5,367,588), and internally reflecting prisms (U.S. Pat. No. 5,377,288). In addition, methods have been described for producing chirped fiber Bragg gratings (U.S. Pat. No. 5,718,738), fiber gratings possessing a continuous sinc- function envelope on a periodic index-of-refraction modulation (U.S. Pat. No. 5,668,901), and methods for impressing an aperiodic grating on an optical fiber (U.S. Pat. No. 5,388,173).

Many present optical communication systems utilize diffraction gratings to enhance their performance. Fiber gratings are, for example, advantageous in wavelength division multiplexing (WDM) systems in which fiber Bragg gratings can provide high reflectivity and high wavelength selectivity with the aim of increasing the transmission capacity of optical

fibers. Complex diffraction gratings can also be used to increase the capacity of optical systems by utilizing a type of multiplexing known as optical code division multiple access (hereinafter OCDMA). OCDMA systems encode different communication channels with different temporal (time) codes as contrasted to the coding in WDM systems in which different channels use different wavelengths of light.

Summary of the Invention

The present invention relates to fiber gratings with complex refractive-index grating profiles, specifically segmented fiber gratings capable of providing programmed spectral filtering with high efficiency. The conventional art does not encompass the segmented fiber gratings pursuant to the present invention. Another aspect of the present invention relates to methods for fabricating segmented fiber gratings. In another aspect of the present invention, the complex fiber gratings are used in an OCDMA optical communication system.

The present invention comprises a structure (i.e., a segmented fiber grating) providing a means of creating a spectrally filtered copy of input optical signals. Segmented fiber grating devices accept an input optical signal and generate a reflected signal having a spectrum that corresponds to the spectrum of the input optical signal multiplied by a fiber-grating-specified spectral filtering function. Fiber grating devices, comprised of one or more segmented fiber gratings according to the present invention, can be used, for example, in OCDMA data links to temporally code optical signals with specific codes to allow multiple coded channels to be simultaneously transmitted through the same link and then decoded into separate channels at the output of the system. The segmented fiber gratings of the present invention can also be utilized in any application area in which the ability to effect programmable spectral filtering is utilized, such as dispersion compensation. The segmented fiber gratings fabricated in accordance with the present invention comprise a series of spatially distinct subgratings arrayed end to end. Each subgrating possesses a periodic array of diffractive structures (elements). The overall transfer function of the segmented fiber grating can be determined by controlling: (a) the spatial periodicity or frequency of each subgrating, (b) the amplitude of each subgrating, (c) the optical distance between the last diffraction element on each subgrating and the first diffraction element of the successive subgrating, and (d) the position and length of each subgrating on the segmented fiber grating.

Brief Description of the Drawings

Figure 1 is an overall diagram of a multiplexing/demultiplexing system utilizing segmented fiber gratings.

Figure 2 is a schematic diagram showing the input and the output directions along which light passes into and out of the segmented fiber grating.

Figure 3 shows a side view of a segmented fiber grating

Figure 4 shows a temporally coded optical pulse, composed of four time slices, that is incident on a segmented fiber grating of four contiguous equal length subgratings.

Figure 5 illustrates a first technique for fabricating segmented fiber gratings according to the present invention.

Figure 6 shows a second technique for fabricating segmented fiber gratings.

Figure 7 shows a third technique for fabricating segmented fiber gratings.

Figure 8 shows a side view of two subgratings of a segmented fiber grating that have a saw tooth blaze. The light and dark stripes correspond to areas of higher and lower refractive index, respectively.

Detailed Description

Figure 1 is an overall diagram of an OCDMA communication system that uses segmented fiber diffraction gratings to perform optical multiplexing and demultiplexing. While the optical beams in the illustrated embodiment are assumed to propagate inside an optical fiber, they may propagate in free space or any other means known in the art without departing from the scope of the present invention. Short-pulse laser 10 generates a coherent beam of light 12. Beam splitter 13 divides the light into two beams 15 and 16. Beams 15 and 16 are each individually modulated by modulators 15a and 16a, respectively, thereby generating modulated beams 15b and 16b. The modulation of each of the beams is achieved in response to an external data stream not explicitly shown in Figure 1. Each of the modulated beams 15b and 16b comprises, either by virtue of the operative character of the laser source 10, the action of the modulators 15a and 16a, or a combination of the two, a stream of bits having a temporal character that matches the designed input pulses of segmented fiber gratings 19 and 20, respectively.

Modulated beams 15b and 16b comprise optical input fields that are directed through optical circulators 15c and 16c along directions 15d and 16d into segmented fiber gratings 19 and 20, respectively. Segmented fiber gratings 19 and 20 generate output optical fields with time codes TC15 and TC16, respectively, that propagate along directions 15d and 16d in the opposite direction of the respective input optical fields. The output optical fields are separated from directions 15d and 16d at the optical circulators 15c and 15d into output beams 15e and 16e, respectively. Whereas the input and output beams 15c, 16e are separated by the optical circulators 15c, 15d in this embodiment, any means known in the art (e.g., a beam splitter, etc.) may be used to separate the counterpropagating input and output beams without departing from the scope of this invention. Output beams 15e and 16e are combined by a beam combiner 22 and output into optical transport 11 (e.g., an optical fiber). (The coding technique and the details of segmented fiber gratings 19 and 20 are described below). The combined coded beam propagating through the optical transport 11 is transported to beam splitter 13a. Beam splitter 13a splits the combined coded beam into two equivalent beams 15f and 16f directed through optical circulators 15g

and 16g at fiber gratings 19a and 20a along directions 15h and 16h, respectively. Segmented fiber gratings 19a and 20a, operative on respective time codes TC15 and TC16, generate respective output optical fields that propagate along directions 15h and 16h in the opposite direction of the respective input optical fields. The segmented fiber gratings 19a, 20a and the optical circulators 15g and 16g produce output beams 15i and 16i, respectively. Output beams 15i and 16i are modulated identically to the corresponding beam 15 and 16, respectively. (The decoding technique and the details of the segmented fiber gratings 19a and 20a are described below). The respective contents of output beams 15i and 16i are detected by detectors 15j and 16j and it is thus reconverted into respective electrical signals that correspond to the signals that activated modulators 15a and 16a.

It is noted that, whereas the embodiment shown in Figure 1 combines two beams into one coded beam, three, four, or more beams could similarly be multiplexed into one beam using OCDMA coding. The resulting combined coded beam can be transmitted over a transmission system. The coded beam can be demultiplexed into the original signals.

Segmented fiber gratings 19, 19a, 20, and 20a are configured to accept light from the input direction and to redirect the light into respective output directions in a manner that is dependent on the temporal waveform of the input light. The fiber environment in which each segmented fiber grating is confined eliminates the need for precise control of input and output beam directions that characterizes many free-space devices capable of providing programmed spectral filtering. The fiber environment enhances the efficiency with which input light energy is transferred to output light energy by eliminating competing output channels that exist in many-free space devices including segmented surface gratings. Considering a specific input waveform, the function of the segmented fiber can be summarized as follows: A portion of each spectral component of the input light field is mapped into the output direction with a controlled amplitude and phase. The fiber grating applies a designated complex-valued spectral filtering to the input optical field and emits the filtered version of the input field in the output direction. The spectral resolution of the filtering function is determined by the physical size of the enabling segmented fiber grating.

Figure 2 shows a segmented fiber grating fabricated in accordance with the present invention. We focus now on the configuration of a single segmented fiber grating. Fiber grating devices incorporating multiple segmented fiber gratings can be configured through repetitive application of single segmented fiber grating procedures. The segmented fiber grating has N spatially distinct subgratings or sections 1 to N. In the embodiment shown, N = 8. An exemplary cross section of the segmented fiber grating is shown in Figure 3. Figure 3 is only presented for illustrative purposes to show that the diffractive structure on each of the subgratings of the segmented fiber grating has independently selectable amplitude and phase. It is noted that, in Figure 3, the dark and light stripes indicate spatial regions of higher and lower values, respectively, of optical refractive index with the understanding that, for illustrative purposes only, between six and nine diffractive elements

are shown per subgrating, although other embodiments can comprise substantially different numbers of elements.

In order to mathematically define the structure of the subgratings contained within one segmented fiber grating, it is necessary to define a set of coordinates descriptive of the segmented fiber grating and associated optical input and output directions. For convenience, we choose the origin of the reference coordinate axes to be situated in the center of the segmented fiber grating and the propagation axis of the fiber to coincide with the x-axis. We define the optical input direction to be in the $+\hat{x}$ direction and the optical output direction to be in the $-\hat{x}$ direction. Figure 2 shows a schematic diagram of a segmented fiber grating structure showing the input and output directions. Some light will be transmitted through the grating in the $+\hat{x}$ direction. In the present embodiment this light is not utilized. However, the transmitted light is also spectrally encoded and the present invention extends to use of such light in suitably modified embodiments.

Fiber grating devices according to the invention may utilize a single segmented fiber grating structure, multiple spatially superimposed segmented fiber grating structures, or a combination of spatially superimposed and spatially separated segmented fiber grating structures fabricated onto a single fiber or multiple fibers.

The fiber grating of Figure 2 is a reflective segmented fiber grating, but all particulars discussed herein can be transferred to a transmissive fiber grating geometry. Furthermore, all of the particulars discussed herein can be transferred to any waveguide geometry, be it semiconductor waveguides, rectangular glass waveguides, or fiber waveguides supportive of segmented gratings. It is noted this fiber grating is arranged along the x-axis and the diffractive elements typically, but not necessarily, span the core (and/or cladding) of the optical fiber in the y-z plane.

A single segmented fiber grating structure is desirably fabricated in the form of a series of N spatially distinct subgratings arrayed end to end and having a collective span that defines the operative length of the segmented fiber grating. Each subgrating possesses a periodic array of diffractive elements arranged sequentially along the fiber axis (x-axis). The spacing between diffractive elements within the N successive spatial subgratings may not necessarily be the same. The N subgratings are written or otherwise created within the overall fiber grating such that each subgrating occupies a specific subsection of the overall fiber grating length and the subgratings are situated in series along the fiber axis. The optical path difference between the last diffractive element of each subgrating and the first diffractive element of the successive subgrating is controlled as will be described.

Control of positioning of diffractive elements provides control over relative spatial phases of adjacent subgratings. Also controlled are the amplitude and period of the diffractive elements within a given subgrating and the length and position of the given

subgrating. The manner in which subgrating parameters is controlled determines the spectral transfer function of the fiber grating. Variation of optical path length between subgratings acts to control the relative phase of light transferred from the input to the output directions. Active devices can be added between the subgratings to dynamically change subgrating-subgrating separation and achieve dynamical reprogramming of the spectral filtering function. Alternatively, active devices can be added between the subgratings to dynamically change the optical path length between subgratings through the introduction of refractive index changes in the regions between subgratings.

The representative segmented fiber grating shown in Figure 3 has eight spatial subgratings. The representative segmented fiber grating is a reflective phase grating, but it could be a transmissive, amplitude, gain, or other generalized physical fiber grating type.

We represent the change in the index of refraction from the effective index of refraction of the fiber (n_o) versus position of one constituent subgrating, labeled by the subscript *i*, of a segmented fiber grating by the following mathematical expression

$$h_i(x) = A_i f_i(2\pi(x - x_i)/\Lambda_i) \qquad \{\text{for } x_i^a \le x \le x_i^b\} \qquad (1)$$

where *x* represents the spatial position coordinate along the fiber, x_i is the spatial position shift of the i^{th} subgrating index of refraction pattern, the function f_i represents a particular index of refraction profile and has an argument that is periodic with period 2π and modulates between the values of 0 and 1, A_i is a real-valued amplitude factor, x_i^a and x_i^b are the edge positions of subgrating *i*, and Λ_i is the spatial period of the i^{th} subgrating. Outside the prescribed spatial interval, $h_i(x) = 0$. The subscript *i* ranges from 1 to N and denotes individual spatial subgratings. By specifying the parameters A_i, x_i, x_i^a, x_i^b, and Λ_i for the subgratings employed, a wide range of spectral filtering functions can be encoded.

The parameters A_i, x_i, x_i^a, x_i^b, and Λ_i necessary to produce specific spectral transfer functions can be chosen in a variety of ways. Assume that a fiber grating is to be constructed that provides a particular spectral transfer function $T(\nu)$ (where ν is the optical frequency) as approximated by N transmission coefficients each of which corresponding to one of N contiguous frequency channels collectively spanning the full non-zero width of $T(\nu)$. To accomplish this, the segmented fiber grating will require approximately N subgratings. We assume that $T(\nu)$ is not zero over a specific spectral region of width $\delta\nu$ centered about the frequency ν_0. To provide filtering with the specified resolution ($\delta\nu$), the subgratings will require a spatial length given approximately by $c/(n_o\delta\nu 2)$ where *c* is the speed of light and n_o is the background effective refractive index of the fiber at center frequency ν_0. The total length of the fiber grating will thus be approximately given by $Nc/(2\, n_o\delta\nu)$ assuming that the subgratings are laid down contiguously ($x_i^a \cong x_{i-1}^b$).

For example, if $\delta\nu$ = 100 GHz, n_o = 1.5 , and N = 8, the complete spatial length of a segmented fiber grating capable of representing $T(\nu)$ will be approximately 0.8 cm.

The parameters (A_i, x_i, x_i^a, x_i^b, and Λ_i) for all of the N subgratings comprising the segmented fiber grating determine its spectral transfer function. Given the subgrating parameters, the spectral transfer function of the segmented fiber grating can be determined. Conversely, given a specific spectral transfer function, the subgrating parameters that must be employed to create a segmented fiber grating with that transfer function can be determined. It should be understood that, while the mathematics presented herein contain certain constraining assumptions in order to facilitate an explanation, the equations can be generalized without departing from the invention.

We first give an expression for the spectral transfer function exhibited by a segmented fiber grating in terms of subgrating parameters. Under the assumptions that: (1) $A_i << 1$, and (2) the N subgratings have equal spatial length ($d = x_i^b - x_i^a$ = constant) and are laid down contiguously ($x_i^a = x_{i-1}^b$), and equal spatial period ($\Lambda_i = \Lambda$ = constant), the spectral transfer function $T(\nu)$ of the segmented fiber grating may be written as a sum over subgrating parameters as follows:

$$T(\nu) = F(\nu)\sum_{i=1}^{N} a_i \exp(j\Phi_i) \tag{2a}$$

where:

$$a_i = A_i \exp(-j2\pi x_i / \Lambda), \tag{2b}$$

$$\Phi_i = \pi n_o (x_i^a + x_i^b)[\beta\nu - 1/(n_o\Lambda)], \tag{2c}$$

and

$$\beta = 2/c. \tag{2d}$$

Here, $F(\nu)$ is the spatial Fourier transform of a subgrating given by

$$F(\nu) = \frac{jC}{N}\mathrm{sinc}(\pi n_o d[\nu\beta - 1/(n_o\Lambda)]), \tag{3}$$

where j is $\sqrt{-1}$, and C is a constant dependent on the index of refraction profile and contains a phase factor dependent on the choice of x-origin. The function sinc(x) is defined as equal to sin(x)/x. In writing Eqs. (2a)-(2d) and (3), it is assumed that the output signal is derived from the plus one diffractive order (m = 1) of the subgratings. Analogous expressions for higher orders can also be obtained. More generally, the subgratings can have different spatial lengths and spatial periods (i.e., $d = d_i$ and $\Lambda = \Lambda_i$) and different spatial Fourier transforms (i.e., $F(\nu) = F_i(\nu)$).

If one wishes to design a segmented fiber grating having a specific transfer function, it is necessary to determine appropriate parameters for each subgrating. To do this one first solves Eq. (2a) for a_i and obtains

$$a_i = \beta dn_o \int_{m/(\beta\Lambda n_o)-1/(2\beta dn_o)}^{m/(\beta\Lambda n_o)+1/(2\beta dn_o)} \frac{T(\nu)}{F(\nu)} \exp(-j\pi n_o[\nu\beta - 1/(n_o\Lambda)](x_i^a + x_i^b))d\nu \quad (3)$$

From Eq. (2b) one finds that A_i is equal to the amplitude of a_i. The quantity x_i determines the phase of a_i as seen in the equations above. The parameter Λ is chosen so that the light of carrier frequency ν_o is maximally diffracted using the generalized Bragg condition $\Lambda n_o = m\lambda_o/2$ where $\lambda_o = c/\nu_o$ is the center wavelength of the desired transfer function, and m is the diffractive order (m = 1 in the embodiment discussed herein but alternative embodiments can utilize other diffractive orders).

For a segmented fiber grating to perform the function of optical cross-correlation between optical input waveforms and a reference optical waveform, the function of the fiber grating should be the complex conjugate of the spectrum of the reference optical waveform. The function of optical cross-correlation here means that the electric field reflected by the fiber represents the temporal cross correlation between: (a) an input optical waveform, and (b) the specific reference optical waveform having a conjugated spectrum that coincides with the spectral transfer function of the fiber grating.

Consider a reference optical waveform having a time profile that is represented as a sequence of N contiguous time slices within which the amplitude and phase of the optical field is constant. In time slice i (I = 1,...,M), the electric field has constant amplitude B_i and phase ϕ_i. The reference waveform is thus determined by the set of complex numbers $[B_1\exp(j\phi_1), B_2\exp(j\phi_2),\ldots,B_M\exp(j\phi_M)]$ along with the optical carrier frequency in each time slice and the overall temporal duration of the waveform. Figure 4 schematically illustrates an input optical waveform of the form $[C_1\exp(j\phi'_1), C_2\exp(j\phi'_2),\ldots,C_4\exp(j\phi'_4)]$ incident on a segmented fiber grating.

When an optical waveform is incident on the fiber grating, the fiber grating will spectrally filter the incident waveform as described by the fiber grating spectral transfer function. If the fiber grating is to perform the function of cross-correlation against the reference optical waveform, the subgratings should have parameters that are the "time-reversed" complex conjugate of the reference optical waveform, e.g., $[a_1, a_2,\ldots, a_8] = [B_8\exp(-j\phi_8), B_7\exp(-j\phi_7),\ldots,B_1\exp(-j\phi_1)]$ where the subgrating parameters are related to a_i by Eq. (2b) given the assumptions in deriving Eqs. (2a-3) are met. The operation of cross-correlation may be used to multiplex and demultiplex optical signals according to the OCDMA scheme.

It is noted that the refractive index profile (functional form of $f_i(x)$ in Eq. (1)) affects primarily the diffraction efficiency of the fiber grating if the approximations used to derive Eqs. (2a-(2d) and (3) are met. This affects the magnitude of the spectral transfer function or the constant C in Eq. (3).

The following specifies the segmented fiber gratings employed in an exemplary two-channel multiplex/demultiplex system as in Figure 1. Fiber gratings 19, 19a, 20, and 20a used are each composed of a segmented fiber grating. Fiber gratings 19 and 20 accept uncoded data streams and launch time-coded data into an output direction. Fiber gratings 19a and 20a accept time-coded data and launch distinct time codes into an output direction while simultaneously stripping off time-coding. Fiber gratings 19a and 20a function through the process of cross-correlation.

In the multiplexer/demultiplexer embodiment presently considered we use sinusoidal refractive index profiles in fiber gratings 19, 19a, 20, and 20a with a fiber grating period of $\Lambda = 0.51$ μm . We assume uniform subgrating amplitudes of $A_l = 10^{-5}$, and $n_o = 1.5$ for all the segmented fiber gratings. The fiber gratings have eight contiguous ($x_i^a = x_{i-1}^b$) subgratings and each subgrating has a length of 1 mm, thus the total grating length is 8 mm. The segmented fiber gratings are configured for optical data streams having a carrier frequency of 195 THz (a carrier wavelength $\lambda = 1.54$ μm).

The segmented fiber gratings 19 and 20 of this embodiment are designed to accept temporally short input pulses of optimal duration $\tau_p = 10$ ps and generate temporally coded pulses along the output direction. The filtering bandwidth of the segmented fiber gratings 19 and 20 is $\delta\nu \cong 1/\tau_p$ or 100 GHz.

For fiber grating 19 to produce output pulses of approximate duration $\tau_p = 80$ ps with the following time code TC15:

[1, 1, 1, exp(j2π/3), exp(j4π/3),1, exp(j4π/3), exp(j4π/3)],

the corresponding subgrating parameters x_i for the segmented fiber grating are:

$[x_1, x_2, \ldots, x_8]$ = [0.0 μm, 0.0 μm, 0.0 μm, - 0.17 μm, 0.17 μm, 0.0 μm, 0.17 μm, 0.17 μm].

For fiber grating 20 to produce output pulses of approximate duration $\tau_p = 80$ ps with the following time code TC16:

[exp(j4π/3), exp(j2π/3), 1, exp(j4π/3), exp(j2π/3), 1, exp(j4π/3), exp(j2π/3)],

the corresponding subgrating parameters x_i for the segmented fiber grating are:

$[x_1, x_2, \ldots, x_8]$ = [0.17 μm, -0.17 μm, 0.0 μm, 0.17 μm, - 0.17 μm, 0.0 μm, 0.17 μm, -0.17 μm].

The multiplexed beams copropagating in optical transport 11 and split at beam splitter 13a may be demultiplexed at fiber gratings 19a and 20a. The demultiplexing fiber gratings 19a and 20a in Figure 1 are identical in design to fiber gratings 19 and 20, respectively, but with the input and output direction on the opposite side of the fiber grating.

The reversal of the propagation direction into the fiber gratings is equivalent to changing $h_l(x)$ in Eq. (1) to $h_l(-x)$, resulting in coded fiber gratings 19a and 20a described below.

In order to produce output pulses of approximate duration $\tau_p = 10$ ps given an input optical field with time code TC15:

[1, 1, 1, exp(j2π/3), exp(j4π/3),1, exp(j4π/3), exp(j4π/3)],

the segmented fiber grating 19a has subgrating parameters x_i given by:

$[x_1, x_2, \ldots, x_8]$ = [-0.17 μm, -0.17 μm, 0.0 μm, -0.17 μm, 0.17 μm, 0.0 μm, 0.0 μm, 0.0 μm].

In order to produce output pulses of approximate duration τ_p = 10 ps given an input optical field with the time code TC16:

[exp(j4π/3), exp(j2π/3), 1, exp(j4π/3), exp(j2π/3), 1, exp(j4π/3), exp(j2π/3)],

the segmented fiber grating 20a has subgrating parameters x_i given by:

$[x_1, x_2, \ldots, x_8]$ = [0.17 μm, -0.17 μm, 0.0 μm, 0.17 μm, -0.17 μm, 0.0 μm, 0.17 μm, -0.17 μm].

For the fiber grating specifications given above, the laser source 10 as shown in Figure 1 must have a maximum temporal pulse width (FWHM) of 10 ps (given by the minimum τ_p of the two segmented fiber gratings).

Manufacturing Segmented Fiber Gratings: Using lithography (optical or electron beam), refractive-index profiles can be written onto a fiber point-by-point along the fiber axis. Thus, segmented fiber gratings with spatial phase shifts between the subgratings can be written directly onto a fiber. Control of subgrating amplitude is also possible using this technique.

It is also possible to use a variety of holographic techniques to successively or simultaneously record subgratings with controlled refractive-index profile properties.

Figure 5 illustrates how a segmented fiber grating can be manufactured by spatial repositioning of the fiber to produce subgratings with controlled spatial phase. The angle between the two beams or the wavelength of the two beams used in standard holographic recording can be used to control the grating spacing Λ_i. Spatial phase shifts may be introduced between exposures by translating the fiber. Thus, the N subgratings can be recorded, as shown in Figure 5, by spatially translating an aperture mask of width d = D/N (where D is the total grating length) by its width N times and exposing the recording material at each mask position. Between exposures, the fiber is shifted along the fiber axis. The fiber is shifted a distance x_i relative to a fixed reference prior to exposure of subgrating i. Control of writing beam intensity between fiber exposures allows for control of subgrating amplitude A_i.

A similar method of producing segmented fiber gratings comprised of subgratings with spatial phase shifts uses single-exposure holography with a phase-code mask having the appropriate subgrating phase shifts encoded in its optical thickness. The mask is placed in one of the two interfering beams in close proximity to the fiber.

Figure 6 shows a holographic method for fabricating fiber gratings with N subgratings with controlled spatial phase shifts. This technique controls the phase-difference, ϕ_i, between the two optical writing beams as shown in Figure 6. Control of writing-beam intensity allows for control of subgrating amplitude as well. The optical phase

difference determines the position of the interference pattern on the fiber where the beams overlap, and their intensity controls the modulation amplitude of the interference pattern. The subgratings are recorded by illuminating the entire sample region with the interference pattern, but using an aperture of width "d" so that only the region behind the aperture is exposed and recorded. By spatially shifting the aperture across the sample in N steps, it is possible to write a series of N subgratings, with each grating having a phase determined by the phase difference ϕ_i used during exposure of the i^{th} subgrating.

Figure 7 illustrates an approach to producing subgratings termed the "master phase mask" approach. In this approach a single writing beam is used in conjunction with a master-phase-mask diffraction grating. A single beam incident on a master grating will be diffracted to yield one or more extra output beams. The incident and diffracted beams will interfere, producing an interference pattern that can be used to record a near duplicate of the master grating. This property of diffraction gratings makes it possible to use a master grating to generate the interference pattern needed for the fiber grating. The phase in each subgrating is imparted by translating the master grating or the recording fiber between successive masked subgrating exposures.

Production of Segmented Fiber Gratings Through Fourier Synthesis: A fiber grating may be made by a Fourier synthesis method by superposition of multiple periodic gratings each of which spanning the entire length of the segmented fiber grating. The constituent periodic gratings have relative phases, amplitudes, and spatial periods such that, when summed, they collectively produce the segmented fiber grating profile of interest. The constituent periodic gratings are the Fourier components of the desired fiber-grating profile. The more Fourier components used, the more sharply defined the subgratings.

The fiber gratings can be manufactured by holographic or lithographic methods. By exposing a photosensitive fiber with multiple holographic exposures (each of which writing a particular constituent periodic grating), the desired fiber- grating profile can be recorded. Lithographic means also provide for multipass writing in which each pass is employed to write one respective constituent periodic grating.

Fiber Gratings With Specific Refractive Index Profiles: By using lithographic and holographic methods, the fiber gratings may have an arbitrary refractive-index-modulation profile that includes saw-tooth blazed, square wave, sine wave, etc., in order to engineer the diffraction efficiency. Figure 8 is a schematic of a fiber grating similar to that shown in Figure 3, but with a saw-tooth modulation profile.

It is noted that the descriptions of the segmented fiber gratings set forth herein can be generalized to include gain fiber gratings as well as absorption fiber gratings.

Dynamic Gratings: In the embodiments described above, the fiber gratings are static. The following describes an embodiment in which the fiber gratings can be dynamically reprogrammed with respect to their spectral filtering functions.

In the previously described embodiments, the spectral transfer function of the gratings is determined by the parameters A_i, x_i, x_i^a, x_i^b, and Λ_i of its constituent subgratings. Generally speaking, any means known in the art that provides for dynamic control of one or more of these parameters will enable dynamic reprogramming of gratings. Various construction methods allow for dynamic reconfiguration of gratings, for example, control of x_i and Λ_i through control of fiber index of refraction or fiber length. A fiber grating created by the means described above may contain a material whose index of refraction can be controlled by any of the standard means known in the art including, for example, applied electric field, pressure, current, temperature, or optical irradiation. A fiber grating may also be created within a system that has spatially localized stretching or compressing of the fiber, thereby changing a combination of x_i^a, x_i^b, x_i, and Λ_i in a way that is determined by the geometry of the system.

While the invention has been described with respect to example embodiments, it will be understood by those skilled in the art that various changes in format and detail may be made without departing from the spirit and scope of the invention.

We claim:

1. A diffractive waveguide structure operative to produce an output optical signal having a spectral profile corresponding to a product of a spectral profile of an input optical signal and a predetermined complex-valued spectral filtering function, the diffractive waveguide structure comprising a plurality of spatially distinct subgratings, each subgrating including a periodic array of diffraction elements.

2. The diffractive waveguide structure of claim 1, wherein each of the subgratings has an amplitude, spatial phase shift, beginning and ending position, and spatial period (A_i , x_i , x_i^a, x_i^b, and $\Lambda_{i,}$, respectively), wherein the amplitude and spatial phase shift of the subgratings are related by

$$a_i = \beta d_i n_o \int_{m/(\beta\Lambda m_o)-1/(2\beta d i n_o)}^{m/(\beta\Lambda m_o)+1/(2\beta d i n_o)} \frac{T(v)}{F_i(v)} \exp(-j\pi n_o[v\beta - 1/(n_o\Lambda_i)](x_i^a + x_i^b))dv$$

wherein A_i , x_i are determined by the amplitude and phase of a_i, respectively, $a_i = A_i \exp(-j2\pi x_i/\Lambda_i)$, $\beta = 2/c$, c is the vacuum speed of light, $d_i = x_i^b - x_i^a$, m_i is the order of the ith subgrating, $F_i(v) = (jC/N)\mathrm{sinc}(\pi n_o d_i[v\beta - 1/(n_o\Lambda_i)])$, and $T(v)$ is the spectral transfer function of the structure.

3. The optical waveguide structure of claim 1, wherein the spectral transfer function of the optical waveguide structure is determined by positions of the subgratings.

4. The optical waveguide structure of claim 1, wherein amplitudes of the various subgratings control the spectral transfer function.

5. The optical waveguide structure of claim 1, wherein subgrating parameters of at least one subgrating are defined by active materials and are dynamically reprogrammable to select the spectral transfer function of the segmented fiber grating, the subgrating parameters selected from a group consisting of optical length, optical transmission and placement.

6. The structure recited in claim 1, wherein the subgratings are transmissive gratings.

7. The optical waveguide structure recited in claim 1, wherein the subgratings are reflective gratings.

8. The optical waveguide structure recited in claim 1, wherein the subgratings are absorption gratings.

9. The optical waveguide structure recited in claim 1, wherein the subgratings are phase gratings.

10. The optical waveguide structure recited in claim 1, wherein the optical waveguide structure is a rectangular waveguide

11. The optical waveguide structure of claim 1, wherein the optical waveguide structure is a cylindrical waveguide or optical fiber.

12. The optical waveguide structure of claim 1, wherein at least one subgrating has a blazed refractive index profile selected to adjust the diffraction efficiency into different diffractive orders of the segmented fiber grating.

13. The diffractive optical waveguide structure of claim 1, wherein the subgratings have respective amplitudes, spatial phase shifts, beginning and ending positions, and spatial periods (A_i , x_i , x_i^a, x_i^b, Λ_i, respectively) and wherein the amplitudes and spatial phase shifts are dynamically controllable to dynamically reprogram the complex-values spectral filtering function.

14. The diffractive waveguide of claim 13, wherein the spatial phase shifts x_i are controllable by varying an index of refraction or a length of fiber separating different subgratings.

15. The diffractive waveguide structure of claim 13, wherein at least one of the spatial periods Λ_i and the amplitudes A_i are controllable by varying indices of refraction of respective subgrating sections by application of an electric field, pressure, strain, electrical current, temperature, optical irradiation, stretching, or compression of the subgratings.

16. An optical waveguide structure that accepts an input optical signal and generates an output optical signal, the output optical signal having a temporal waveform corresponding to a temporal waveform of a reference optical signal, the optical waveguide structure comprising a segmented fiber grating that includes a plurality of subgratings, the segmented fiber grating having a spectral transfer function such that a product of the spectral transfer function with a spectrum of the input optical signal corresponds to the spectrum of the reference optical signal.

17. An optical waveguide structure that receives an optical input signal and generates an optical output signal, the optical output signal having a temporal structure corresponding to a cross-correlation of the input optical signal with a reference optical waveform, the waveguide structure comprising a segmented fiber grating that includes a plurality of subgratings, wherein a spectral transfer function of the segmented fiber grating is determined by the reference optical waveform.

18. A system for optical code division multiple access (OCDMA) that multiplexes and demultiplexes a plurality of optical signals defining distinct data streams onto a common transport channel, wherein the distinct data streams are distinguished based on impressed optical time codes, the system comprising:

(a) a source of a plurality of optical data streams;

(b) an OCDMA multiplexer situated and configured to receive the plurality of optical data streams, direct the optical data streams to respective encoding segmented fiber

gratings, and produce an encoded output beam encoded according to time codes defined by the encoding segmented fiber gratings;

(c) an OCDMA demultiplexer situated and configured to receive the encoded output beam and direct the encoded output beam to a plurality of decoding segmented fiber gratings, the decoding segmented fiber gratings having respective spectral transfer functions determined by subgrating parameters A_i, x_i, x_i^a, x_i^b, and Λ_i and corresponding to respective selected optical time codes, wherein at least one of the decoding segmented fiber gratings produces an optical signal corresponding to a cross correlation of an optical data stream with a selected time-code.

19. A method of applying a specified complex-valued spectral filtering function to a light signal by passing the light signal into a structure that includes a plurality of spatially distinct subgratings, each subgrating possessing a periodic array of diffractive elements, the subgratings combining to form a segmented fiber grating that applies the specified complex-valued spectral filtering function.

20. A method of applying a specified temporal waveform onto an input light signal by passing the light signal into a structure that includes a plurality of spatially distinct subgratings, each subgrating possessing a periodic array of diffractive elements, the subgratings combining to form a segmented fiber grating programmed to produce the specified temporal waveform.

21. A method of producing an output optical signal in response to an input optical signal, the output optical signal corresponding to a cross-correlation of a reference optical waveform with the input optical signal, the method comprising passing the input optical signal into a structure that includes a plurality of spatially distinct subgratings, each subgrating having a periodic array of diffractive elements, the subgratings combining to form a segmented fiber grating with a transfer function determined by a complex-conjugate of a Fourier spectrum of the reference optical waveform.

22. A method for fabricating a diffractive waveguide structure including a plurality of subgratings, comprising:

(a) defining a sensitized length of an optical waveguide;

(b) illuminating the optical waveguide along a selected section of the sensitized length, thereby writing a refractive-index profile extending over at least a portion of the selected section of the sensitized length to form a first subgrating; and

(c) repeating step (b) at a different selected section of the sensitized length to create a second subgrating that is spatially distinct from the first subgrating.

23. The method of claim 22, wherein:

step (b) includes

(i) placing a grating mask to cover at least the selected section of the sensitized length, the grating mask comprising a plurality of refractive index perturbations;

(ii) placing an aperture mask between the grating mask and the optical waveguide; and

(iii) illuminating the waveguide through the grating mask and aperture mask, thereby forming a series of refractive index variations defining a subgrating, wherein the illuminated region of the waveguide is determined by the aperture; and

step (c) includes

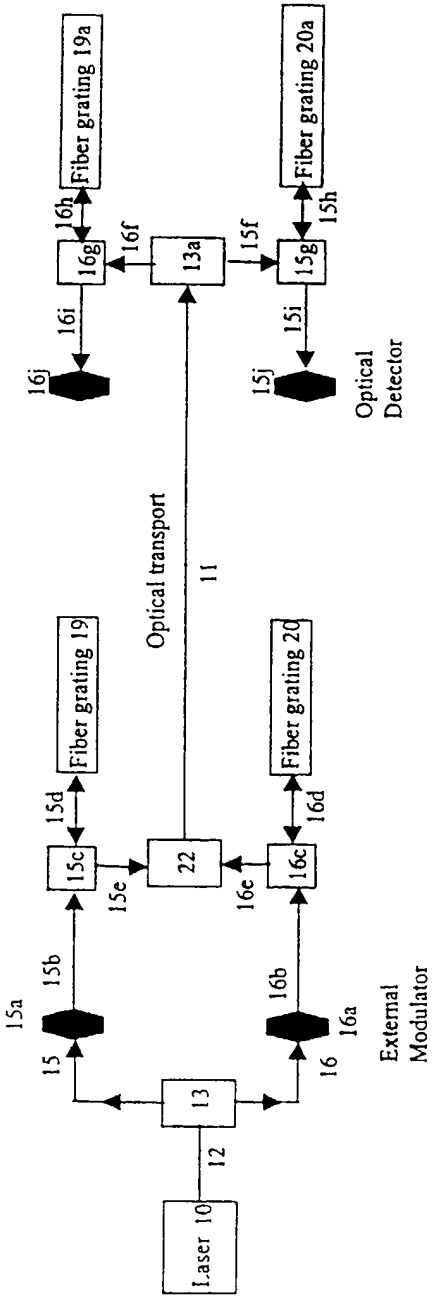
(i) translating the aperture mask to the second selected section, the aperture mask translation having a magnitude on the scale of the aperture width; and

(ii) introducing a relative translation of the optical waveguide and the grating mask to produce a predetermined shift of an optical intensity pattern on the optical waveguide, the magnitude of the shift being less than or equal to a periodicity of either the first or the second subgrating.

24. The method of claim 22, wherein the refractive index profile of step (b) is written by overlapping and interfering at least two optical beams.

25. The method of claim 24, wherein an optical intensity pattern for illumination of the first and second selected sections is determined by adjusting a relative phase shift between the optical beams.

26. The method of claim 23, wherein an illumination time or an optical intensity is independently determined for the first and second selected locations.


Laser 10
12
13
15
15a
15b
16
16a
16b
External Modulator
15c
15d
15e
16c
16d
16e
22
Optical transport
11
13a
16f
16g
16h
16i
16j
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15i
15j
Optical Detector
Fiber grating 19
Fiber grating 20
Fiber grating 19a
Fiber grating 20a

Figure 1

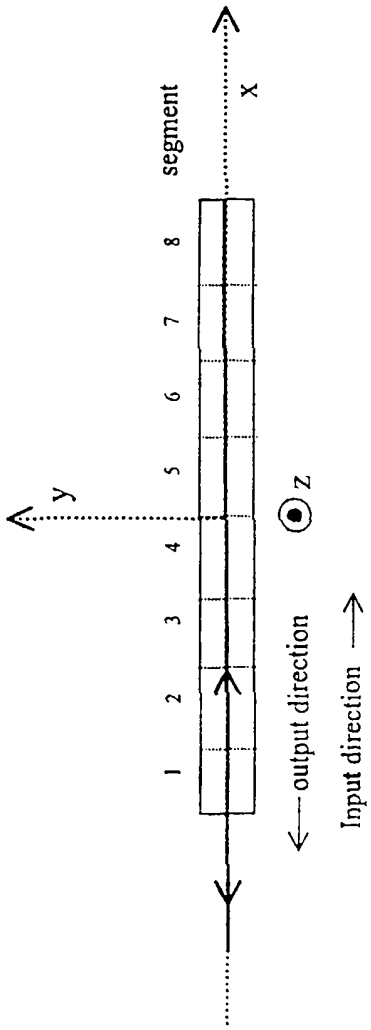

Figure 2

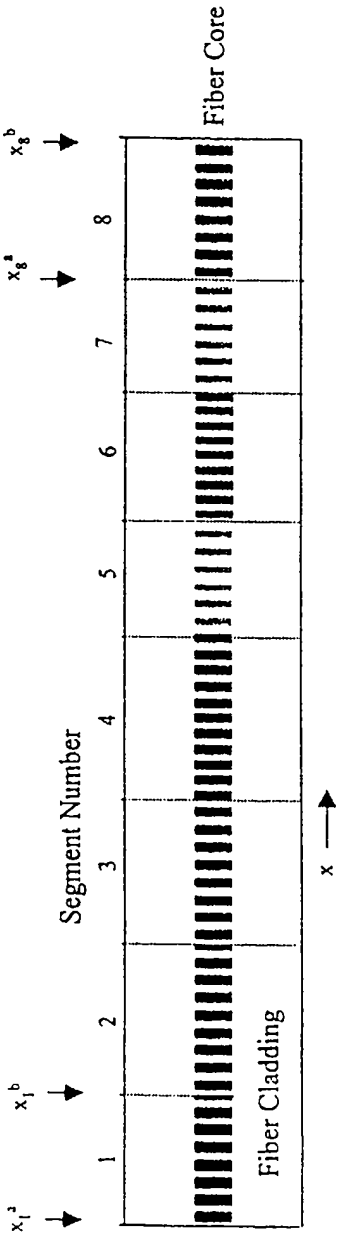

Figure 3

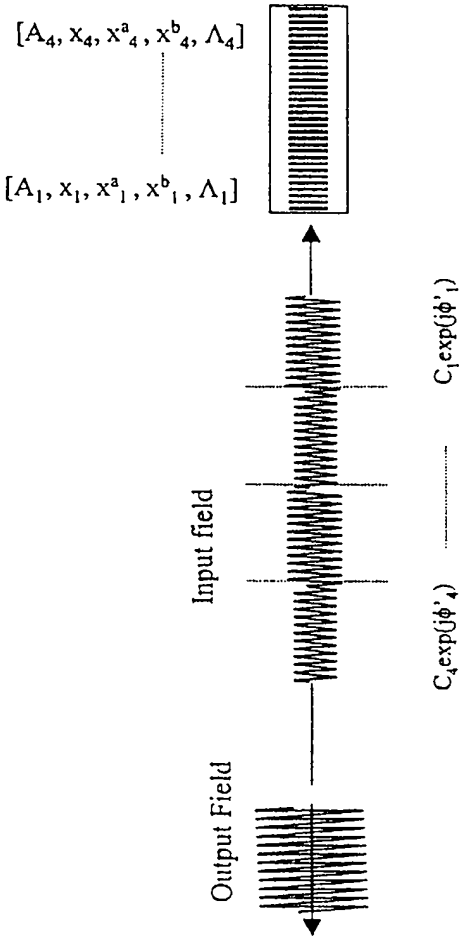
[A4, x4, xa4 , xb4, Λ4]
[A1, x1, xa1 , xb1 , Λ1]
C1exp(jφ'1)
C4exp(jφ'4)
Input field
Output Field

Figure 4

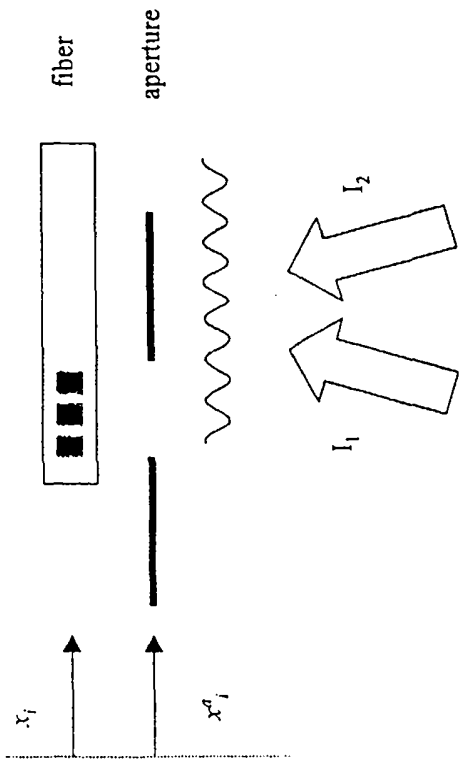

Figure 5

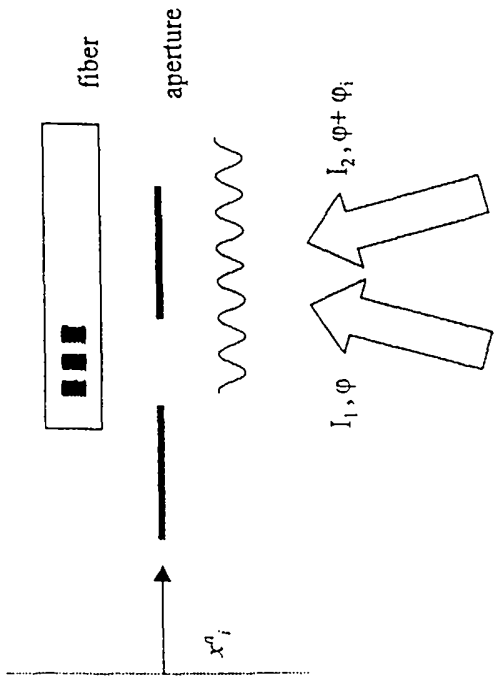

Figure 6

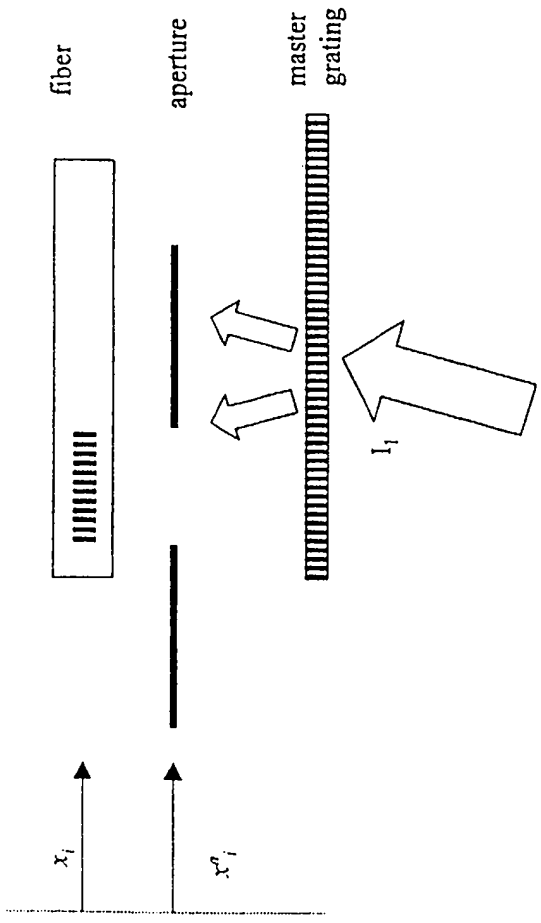

Figure 7

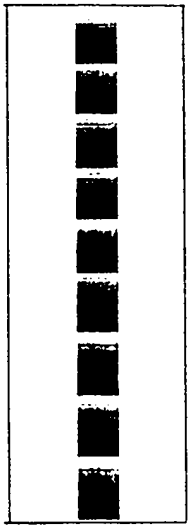

Figure 8

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US99/13954

A. CLASSIFICATION OF SUBJECT MATTER

IPC(6) :G02B 6/34; H04J 14/02
US CL :385/37, 24, 123; 359/130, 115, 569
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 385/37, 24, 123; 359/130, 115, 566, 569, 571, 572, 575

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 5,748,814 A (PAINCHAUD ET AL) 05 May 1998 (05/05/98), see entire document, espcially lines 43-47 of column 4 and lines 43-45 of column 5.	1, 3, 4, 11, 12, 22-24, 26
X	US 5,748,350 A (PAN ET AL) 05 May 1998 (05/05/98), See entire document, especially Figs. 7A-7B, 8A-8B, 10A-10B, and lines 19-25 of column 10.	1, 3-12, 16-21
Y	US 5,726,785 A (CHAWKI ET AL) 10 March 1998 (10/03/98), see entire docuent.	13-15
A, P	US 5,812,318 A (BABBITT ET AL) 22 September 1998 (22/09/98), see claims.	1, 18-21

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

*	Special categories of cited documents:	"T"	later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"A"	document defining the general state of the art which is not considered to be of particular relevance	"X"	document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"E"	earlier document published on or after the international filing date	"Y"	document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"L"	document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)	"&"	document member of the same patent family
"O"	document referring to an oral disclosure, use, exhibition or other means		
"P"	document published prior to the international filing date but later than the priority date claimed		

Date of the actual completion of the international search 27 AUGUST 1999	Date of mailing of the international search report 27 OCT 1999
Name and mailing address of the ISA/US Commissioner of Patents and Trademarks Box PCT Washington, D.C. 20231 Facsimile No. (703) 305-3230	Authorized officer HEMANG SANGHAVI Telephone No. (703) 305-3484

Form PCT/ISA/210 (second sheet)(July 1992)*

ENSDOCID <WO 9967668A1 I >

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US99/13954

Box I Observations where certain claims were found unsearchable (Continuation of item 1 of first sheet)

This international report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:

2. ☐ Claims Nos.:
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:

3. ☐ Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box II Observations where unity of invention is lacking (Continuation of item 2 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

Please See Extra Sheet.

1. ☒ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.

2. ☐ As all searchable claims could be searched without effort justifying an additional fee, this Authority did not invite payment of any additional fee.

3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:

4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

Remark on Protest

☐ The additional search fees were accompanied by the applicant's protest.

☒ No protest accompanied the payment of additional search fees.

BNSDOCID <WO 9967688A1 >

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US99/13954

BOX II. OBSERVATIONS WHERE UNITY OF INVENTION WAS LACKING
This ISA found multiple inventions as follows:

This application contains the following inventions or groups of inventions which are not so linked as to form a single inventive concept under PCT Rule 13.1. In order for all inventions to be searched, the appropriate additional search fees must be paid.

Group I, claims 1-17 and 19-21, drawn to a diffractive waveguide structure.
Group II, claim 18, drawn to a system for optical code division multiple access (OCDMA).
Group III, claims 22-26, drawn to a method of fabricating a diffractive waveguide structure.

The inventions listed as Groups I-III do not relate to a single inventive concept under PCT Rule 13.1 because, under PCT Rule 13.2, they lack the same or corresponding special technical features for the following reasons: The claims of these three groups are directed to different inventions which are not so linked to form a single general concept. The claims in the different group do not have in common the same or corresponding "special technical features". In particular, the diffractive waveguide structure of Group I is completely different from that of Group II which includes the optical code division multiple access system and Group III which includes a method of fabricating the diffractive waveguide structure.

ENSDOCID <WO 9967668A1 I >